Fermi National Accelerator Laboratory

FERMILAB-Pub-89/102-A
March 1989

Coalescing Neutron Stars, Naked Neutrino Bursts, Gamma Rays Gravitational Radiation, Millisecond Pulsars and r-Process Nucleosynthesis

David Eichler
Department of Physics, Ben Gurion University, Beer Sheva, Israel
and
Astronomy Program, University of Maryland, College Park, Md, USA

Mario Livio
Department of Physics, The Technion, Haifa, Israel

Tsvi Piran
Racah Institute for Physics, Hebrew University, Jerusalem, Israel
and
Princeton University Observatory, Princeton, NJ, USA

David N. Schramm
University of Chicago
and
NASA/Fermilab Astrophysics Center
Batavia, Illinois

Submitted to **Nature**, March 1989

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

Coalescing neutron stars may be the most promising sources of detectable gravitational radiation.[1] It has been recently advocated that one can measure the Hubble constant using the gravitational radiation emitted by such sources[2] Clark, van den Huevel and Sutanyou[3] estimated that the rate of formation of close neutron star close binaries is $3 \pm 1.6 \cdot 10^{-4} y^{-1}$ in the galaxy. However this frequency is highly uncertain. In this letter we note that such events could yield the r-process elements if they occur with sufficient frequency. [4] We also propose that such a process would yield naked neutrino bursts[5] which have a distinct gamma ray signature and those might be observed as a subclass of gamma ray bursts. It is remarkable that the above estimate for the rate of these events yields the observed amounts of r-process elements and the observed rate of gamma ray bursts. We also mention that such events may be related to millisecond pulsars formed by collapse of rapidly rotating white dwarfs [6]

The binary pulsar system will coalesce in roughly 10^8 yr using this fact together with the pulsar birth rate and the observation of one close binary pulsar in 300 one can to estimate the formation rate. With 450 pulsars observed now their estimate should be decreased by a factor of 1.5 but this will not change our discussion. The natural progenitor for a close neutron star binary system is a massive x-ray binary. Clark et al.[9] estimate that the probability of disruption of such a pair in the supernova of the secondary is 0.1-0.2 and this leads to a formation rate that agrees with the one based on pulsar statistics. Alternatively, neutron stars that formed in separate events might become attached in dense globular cluster[7]. These mechanisms lead to roughly equal mass binaries with both neutron stars of $1.4M_\odot$.

On the other hand a separate class of neutron star binaries that begin very close might have escaped detection because of their short decay time τ_{gr}, via gravitational radiation. For example, it has recently been suggested by Grindlay and Bailyn [6] that millisecond pulsars arise from accretion induced collapse of white dwarfs in binaries.[7] These authors argue on statistical grounds that low mass X-ray binaries are too rare to be the progenitors of millisecond pulsars, as had been previously proposed.[8] Since the white dwarfs are likely to be spun up to maximum angular momentum, the collapse to a neutron star is likely to "fizzle," and become two neutron stars in orbit around each other[9]. Is not unlikely that the two neutron stars have significantly different masses.

Essentially for all equations of state, the less massive component has a larger radius, [10] R_2, Since it also has the smaller Roche lobe radius, R_L, it is invariably the lighter component (the secondary) which fills first its tidal lobe. Once the secondary fills its Roche lobe, mass transfer ensues. If $\zeta_2 \equiv (\frac{\partial \ln R_2}{\partial \ln M_2})_{ad} > \zeta_L \equiv (\frac{\partial \ln R_L}{\partial \ln M_2})_t$ the mass transfer is dynamically stable while $\zeta_2 < \zeta_L$ results in unstable mass transfer. The latter situation arises when the donor neutron star is comparable or only slightly smaller in mass than the larger. A high initial mass ratio will result in a stable mass stripping process.

Clark and Eardley[1] discussed the evolution of a close neutron star binary. In systems which are unstable to dynamical timescale mass transfer, the margin by which the less massive neutron star overfills its lobe first grows until the orbital evolution is dominated by mass exchange (rather than by gravitational radiation), whose timescale[11] Δt_{ex} is $\sim 6ms$ for masses of $M_1 = 1.4M_\odot, M_2 = 1.2M_\odot$, Once the mass transfer timescale becomes shorter than the gravitational radiation timescale, mass loss accelerates rapidly. In a three-dimensional simulation of this process for a doubly degerate binary system, it is found that *the lighter component is completely dissipated in a little more than two orbital periods* ($\sim 4ms$ in our case). The secondary is transformed into a thick axially symmetric disk orbiting around the primary. Such configurations for the double white dwarf case have been recently constructed by Mochkovitch and Livio[13]. In the calculation of Benz et al.,[12] about 0.3% of the total mass escaped the system. A similar fraction can be expected in our case, since it depends mainly on the surface potentials of the two stars and is thus proportional to $(1 - M_2 R_1 / M R_2)$.

The calculations of Benz et al.[12] and Mochkovitch and Livio [13] have shown the collapse does not result immediately (in the double white dwarf case) even though the total mass exceeds the Chandrasekhar mass. This is mainly a consequence of centrifugal support (the value of kinetic to gravitational energy, also indicates stability). Thus, the late stage evolution of the configuration depends crucially on transport and disposal of angular momentum from the disk. If angular momentum transport occurs entirely by means of degenerate matter vicscosity[14] then extremely long viscous timescales are obtained. Mochkovitch and Livio [13] have shown, however, based on the value of the Reynolds number, that turbulence may arise in significant fractions of such a disk. In this case, the relevant viscosity may be turbulent viscosity $\nu_{turb} \simeq 2 \times 10^9 cm^2 s^{-1} (\frac{V_t}{10^8 cm s^{-1}})(\frac{l_t}{10^5 cm})(\frac{R_e^c}{5000})^{-1}$ where l_t and v_T are typical size and velocity of a turbulent cell and R_e^c is the critical Reynolds number. Such a turbulent disk will transport angular momentum on a timescale $\tau_{vis} \simeq 500 (\frac{R}{10^6 cm})^2 (\frac{\nu_{turb}}{2 \times 10^9 cm^2 s^{-1}})^{-1} sec.$

If the binary is stable ($\zeta_2 > \zeta_L$) against dynamical timescale mass transfer (e.g. if the initial mass ratio is large), the mass transfer rate will approach asymptotically a value dictated essentially by gravitational radiation [15] $\dot{M}_2 \simeq -\frac{2M_2}{(\zeta_2 - \zeta_L)\tau_{gr}}$. This accretion rate is enormous and it raises again the question of disposal of angular momentum and of the ability of the accreting neutron star to accomodate the enormous mass influx as discussed above.

Incidentally the stable mass transfer case leads to another interesting possibility. Neutron stars have a minimum mass below which they are unstable to free expansion. In the present context, the mass losing component may be stripped to the minimum mass before colliding with the more massive one and at this stage it will explode[16]

An interesting feature of the decompression of the secondary is the accompaning deneutronization of the material. One expects the neutrons to collect into large droplets, as is the case, say for decompressing water[17] The beta timescale, assuming neutron-proton Fermi energy differential in the neutron rich nuclei to be of order a few MeV, or on the timescale of a few milliseconds near the neutron drip line comparable to the decompression timescale. Hence the deneutronization is non-adiabatic. This would have two important implications.

First, the decompression can occur while the nuclei are far from the valley of beta instability, and it is a potential r-process site, as suggested by Lattimer and Schramm[4] and Symbalisty and Schramm[18]. Lattimer et al. and Meyer[17] have pointed out that such a process can produce the r-process nuclei with the neutron magic number induced r-process abundance peaks [19] occurring in the observed mass range. This is particularly interesting since these abundance peaks are observed to be quite narrow and distinct from the corresponding s-process abundance peaks. More conventional r-process models involving supernova explosions require fine tuning of temperature and neutron densities in a multitude of different dynamical events to produce such sharp peaks[20]. On the other hand neutron star decompression could achieve the sharp peaks via intrinsic nuclear physics and not have to rely on hydrodynamic concordance in different events.

Neutron capture is extremely rapid and throughout most of the decompression the nuclei are kept very close to the neutron drip line. However, because the β-decay timescale there is comparable to the expansion timescale, there is a significant amount of radioactive heating, the temperature may be of order 1 MeV throughout most of the decompression phase, and the actual neutron excess may be somewhat below that of the zero temperature neutron drip line, as required by the location of the r-process peaks.

Secondly, the anti-neutrinos should be emitted at an energy of up to order MeV ranging up to several MeV. Furthermore the β-decays are usually to MeV level excited states which rapidly emit gamma-ray cascades on their way to the valley of stability.

At the larger neutron star, accreting most of its companion over a timescale of order 10^{-2}s, energy is liberated at a rate of order 10^{54} erg s^{-1}, and copious neutrino emission is expected. The rate of mass infall onto the primary neutron star is within an order of magnitude of that expected in spherically symmetric core collapse scenarios, so the neutrino spectrum, which is buffered by energy dependent interaction cross sections, should resemble the (now measured) burst from a core collapse. Note that in this case here the matter on the envelope is hottest and it is easier for the neutrinos to diffuse. The diffusion timescale for the neutrinos is of order 1 s, but because the distribution of infalling material is biased towards the orbital plane, neutrinos may escape out of the plane on a significantly shorter timescale. Altogether,$\sim 10^{53}$ ergs are expected from the accretion onto the primary neutron star, a sixth of which are electron neutrinos (unfortunately, such neutrinos could not be detected with existing detectors beyond $\sim$ 100 kpc). About 10^{51} ergs in anti-neutrinos are expected from the deneutronization of the companion during its decompression.

The electron type neutrinos from the accreting neutron star and the anti-neutrinos from the disrupted one can pair-produce at suitably triangulated points out of the orbital plane. The efficiency with which the anti-neutrinos are converted is roughly[23]

$$\epsilon = 7 \cdot 10^{-3} \alpha f [(\sigma_{\nu\bar{\nu}}/10^{-44} cm^2)(\bar{E}_\nu/10MeV)^2][\frac{(E_\nu/10^{53} ergs)}{(\bar{E}_\nu/10MeV)}](R/10^6 cm)^{-1}(\tau/0.1sec)^{-1}$$

where $\sigma_{\nu\bar{\nu}}$ is the cross section for $\nu\bar{\nu} \rightarrow e^+e^-$, E_ν is the total energy emitted in neutrinos, $\bar{E}_\nu$ is the average energy of a neutrino; R is the size of the region where the neutrino flux is large and τ is the duration of the neutrino burst; α is a geometrical factor that depends on the geometry of the neutrinosphere and f is the filling factor of the system.

The total energy converted to pairs and, ultimately, the time profiles of the neutrino emission make this estimate rather uncertain. The primary gamma cascades accompanying the β-decay anti-neutrinos should be within an order of magnitude in energy thus $\geq 10^{50}$ ergs.

A comparable or larger gamma ray flux might be produced from pair production by ν - $\bar{\nu}$ pairs emerging from, say, opposite sides of the massive neutron star, though the geometry is less favorable. the greater total energy and the greater compactness may more than compensate for it. Here the key uncertainty is the matter that presumably envelopes the more massive neutron star as it accretes onto it. Since this matter is intensely heated by its own radioactivity, we cannot draw too many parallels with previously worked out catastrophic mass transfer scenarios. In order that the gamma rays emerge before complete degradation, they must be produced beyond the accretion column, and this may require too small an intersection angle between the neutrino and anti-neutrino trajectories to sustain a center of mass energy comfortably above 2 $m_e c^2$.

The gamma ray fireball has such a large compactness parameter, that any soft photons produced within are Compton upscattered and kinetic equilibrium is attained with the remaining pairs. The fireball is optically thick as long as $T > 10^9 K$ and pairs are produced. The fireball will expand until a vast majority of the pairs have annihilated irreversibly, and it becomes optically thin. While the photons are redshifted during the expansion in the frame of the co-moving fluid, the bulk expansion at the onset of transparancy blue-shifts them in the frame of the observer by the same factor. The overall spectrum will be a modified black body with the initial temperature but with fewer hard photons.[21] A big uncertainty in the actual results of the fire ball stems from the potential appearance of a thick baryonic wind. If a large amount of matter is mixied with the fireball most of the available energy will go to its acceleration and the gamma ray signal will not be that strong.

For a luminosity of 10^{47} erg s^{-1} emitted from a region of size 2×10^7 cm, the typical temperature is just about 10^9 K. The spectrum and timescale should be rather like that of a typical gamma ray burst. Since the Universe is transparent to soft gamma rays, [22] it should be detectable to ~ 100 Mpc with fluences typical of gamma ray bursts (10^4 eV/cm^2) if the energy output is of order 10^{46} ergs. However, we do not expect it to have cyclotron absorption features nor a significant non-thermal tail above several MeV. Each of these features are a relatively common feature among gamma ray bursts hence the scenario we propose can explain at most a proper subset of them, i.e. "featureless" gamma ray bursts. These featureless bursts would be extragalactic and thus isotropic. Statistics on featureless gamma ray bursts thus can provide an estimate of the rates of neutron star coalescence events.

In numerical models of cataclysmic mass transfer, some small fraction ($\sim 0.3\%$) of the transferred mass is driven to infinity. It is possible that the radioactive heating, which can supply about 3×10^{-3} Mc^2, can cause most of the disrupted star to explode and escape to infinity. There is about 10^5 $M_\odot$ per galaxy in all material that might be r-process classified and a few 10^3 $M_\odot$ in the heavy r-process material that might be favored in this type of event. If we assume that about $0.3\% M_\odot$ is ejected per event, then they need to occur at a rate between $3 \cdot 10^5$ and $3 \cdot 10^7$ times per galaxy per Hubble time (the first number is if we wish to explain the heavy r-process material and the second one if we want to explain all r-processed material in this way) These rates nicely bracket the rate predicted by Clark of $3 \cdot 10^{-4}$ events per year per galaxy. If a subset of these events is also to account for millisecond pulsars, then we require only about 10^{-5} events per year, or 10^5 per galaxy per Hubble time. Here we have assumed an average spin down time for a typical millisecond pulsars of 10^9 years, and that there are currently about 10^4 millisecond pulsars in our galaxy.

The scenario makes two simple observational predictions: 1) Assuming that $\sim 10^5$ galaxies are within 100 Mpc and that the bursts are indeed detectable out to that distance, then an occurrence of $\approx 10^{-4}$ per galaxy per year yields a detection rate of 10 per year. With the OSSE experiment on the Gamma Ray Observatory, it will be relatively straightforward to distinguish featureless, highly thermal gamma ray bursts from the others. Should such a class be identified, we suggest it would be worthwhile checking for identifications of featureless gamma ray bursts with galaxies. 2) Gravitational radiation events of this nature should be detectable with a 30σ signal up to a distance of 100 Mpc and with a 3σ signal up to a distance of 1000Mpc by the proposed Caltech-MIT Gravitational Wave Detector.[2] The rate of the stronger events should be comparable to the gamma ray bursts of this kind and coincidence of such gamma ray bursts with gravity waves may in fact provide the most stringent observational test of the scenario. If verified it could help prove this as the astrophysical site for the r-process.

We thank J. Goodman, B. Paczynski and B. Meyer for helpful discussions. This work was supported in part by NASA NAGW-1321 and the NSF AST 85-15447 at Chicago and at Maryland by the NASA NAGW 1340 Fermilab Astrophysics Center and by BSF at Jerusalem. We thank the Jerusalem Winter School for hospitality where this work was begun. D.N. Schramm and D.F. Eichler thank the IAS at Princeton and T.Piran thanks the Princeton University Observatory for hospitality while this work was written.

References

1. Clark, J.P.A. and Eardley, D.M. 1977. *Ap. J.*, **215**, 311.
2. Shutz, B.F.,(1986) in Gravitational Collapse and Grativity, Eds. Sato, H. and Nakamura, T., World Scientific Publications, Singapore.
3. Clark, J.P.A., van den Huevel, E. P.J. and Sutantyo, W.(1979)*Astro. and Astrophys.* **72**, 120.
4. Lattimer, J. and Schramm, D.S. (1976) *Ap. J.*, **210**, 549.
5. Berezinsky, B. and Prilutski, P.(1985) *Proc. 19th Internatinal Cosmic Ray Conference, La Jolla.*
6. Grindlay, J.E. and Bailyn, C.D. (1988) *Nature* **336** 48.
7. Ostriker, J.P. (1979) Sources of Gravitational Radiation, Ed. Smarr, L.L. *Cambridge University Press* Cambridge, England.
8. Alpar, M.A., Cheng, A.F., Ruderman, M.A. and Shaham, J. (1982) *Nature* **300**, 708.
9. Clark, J.P.A. (1979) Sources of Gravitational Radiation, Ed. Smarr, L.L. *Cambridge University Press* Cambridge, England.
10. Arnett, W.D. and Bowers, R.L. 1977, *Ap. J. Suppl.*, **33**, 415.
11. Webbnik, R.F. (1984) *Ap. J.*, **277**, 355.
12. Mochkovitch. R. and Livio, M. (1989) *Astron. Ap.*,**209**, 118.
13. Benz, W., Bowers, R.L., Cameron, A.G.W. and Press, W.H. (1989), *Ap. J.*, in press.
14. Itoh, N., Kohyama, Y. and Takenchi, H. 1987, *Ap. J.*, **317**, 733.
15. Webbink, R.F. and Iben, I Jr. 1987, in *IAU Colloq. 95, The Second Conference on Faint Blue Stars*, eds. A.G. Davis Philip, D.S. Hayes and J.W. Liebert (Schenectady : L. Davis Press),p.455.
16. Page, D.N., (1982) *Phys. Lett. A.*, **91**, 201, Piran, T. and Hut, P., (1982) *Talk given at the Numerical Astrophysics conference in honor of J.Wilson*, Urbana IL. unpublished.; Colpi, M., Shapiro, S.L. and Teukolsky, (1989) *Ap. J.* in press.
17. Lattimer, J.M. Mackie, F., Ravenhall, D.G. and Schramm D.N. (1977)*Ap. J.* **213** 225; Meyer, B. (1989) *Ap. J.* in press.
18. Symbalisty, E.M.D. and Schramm D.N. (1982) *Astrophys Lett.* **22**, 143.
19. Burbidge, E.M., Burbidge C.A.. , Fowler, W.A. and Hoyle, F. (1957) *Rev. Mod. Phys.* **29**, 547.
20. Norman, E. and Schramm D.N. (1979) *Ap. J.* **228** 88, Cameron, A.G.W., Cowan, J. and Truran, J. (1983) **Nucleosynthesis** Ed. D. Arnett and J. Truran *University of Chicago*.
21. Goodman J. (1986) *Ap. J. Lett.* **308**, L47; Paczynski, B. (1986) *Ap. J. Lett* **308**, L43.
22. Babul, A., Paczynski B., and Spergel D.N.(1987) *Ap. J. Lett.* **316**, L49; Paczynski, B. (1988) *AP. J* **333** 694; Paczynski, B.(1988) *Ap. J.* **335**, 525. Shapiro, S.L. and Tevkolsky, S.A. 1983, in *Black Holes, White Dwarfs and Neutron Stars*, (New York : John Wiley Sons), p.477. Canuto, V. 1975, *Ann. Rev. Astr. Ap.*, **13**, 335.
23. Berezinsky, V. and Prilutsky, D. (1987) *Proc. Int. Cosmic Ray Conf.* Moscow.